

HIGH-EFFICIENCY DEVICE RESEARCH

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HIGH-EFFICIENCY SILICON SOLAR CELLS

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**ORGANIZATION: JOINT CENTER FOR GRADUATE STUDY
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DAN DOYLE****Objectives and Approach****OBJECTIVES**

- ACHIEVE AN AMI EFFICIENCY $> 19\%$.
- IDENTIFY LIMITING CURRENT MECHANISMS FOR HIGH EFFICIENCY CELLS.
- INVESTIGATE APPROACHES FOR PASSIVATING SURFACES OF SILICON SOLAR CELLS.

APPROACH**SILICON MINP SOLAR CELLS**

- INCREASE J_{PH} TO 36 mA/cm^2 WITH $\text{TiO}_2/\text{MgF}_2$ DBLAR AND BY USING COLLECTOR GRID WITH 4% SHADOWING.
- OPTIMIZE EMITTER DONOR CONCENTRATION PROFILE TO MINIMIZE CURRENT LOSSES.

CURRENT LOSS MECHANISMS

- CONDUCT TEMPERATURE-DEPENDENT I-V ANALYSES TO IDENTIFY CURRENT LOSS MECHANISMS.
- MODELING CALCULATIONS FOR INTERPRETING EXPERIMENTAL RESULTS.

SURFACE PASSIVATION

- INVESTIGATE PECVD SiN_x FOR PASSIVATION OF SILICON.
- DETERMINE SURFACE RECOMBINATION VELOCITY FROM PHOTORESPONSE.
- DETERMINE D_{ss} FROM CAPACITANCE MEASUREMENTS ON HIGHLY DOPED N-TYPE WAFERS AND ON N^+ SURFACES OF N^+/P CELLS.

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Surface Passivation Studies

SURFACE STATE DENSITY

DETERMINE D_{ss} FROM HIGH FREQUENCY AND SLOW RAMP MEASUREMENTS WITH Al GATES.

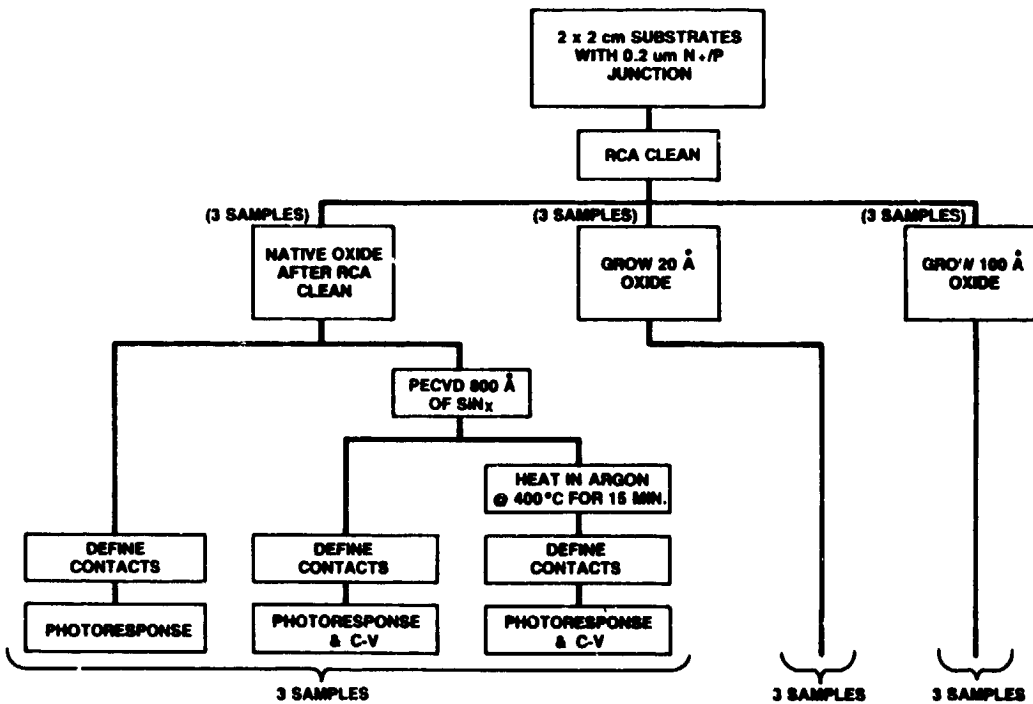
- 2 ohm-cm ($N_A = 7 \times 10^{15} \text{ cm}^{-3}$) P-TYPE
- 0.2 ohm-cm ($N_A = 2 \times 10^{17} \text{ cm}^{-3}$) P-TYPE
- .08 ohm-cm ($N_D = 7 \times 10^{17} \text{ cm}^{-3}$) N-TYPE
- .01 ohm-cm ($N_D = 5 \times 10^{18} \text{ cm}^{-3}$) N-TYPE

MODIFIED ROSIER MEASUREMENT

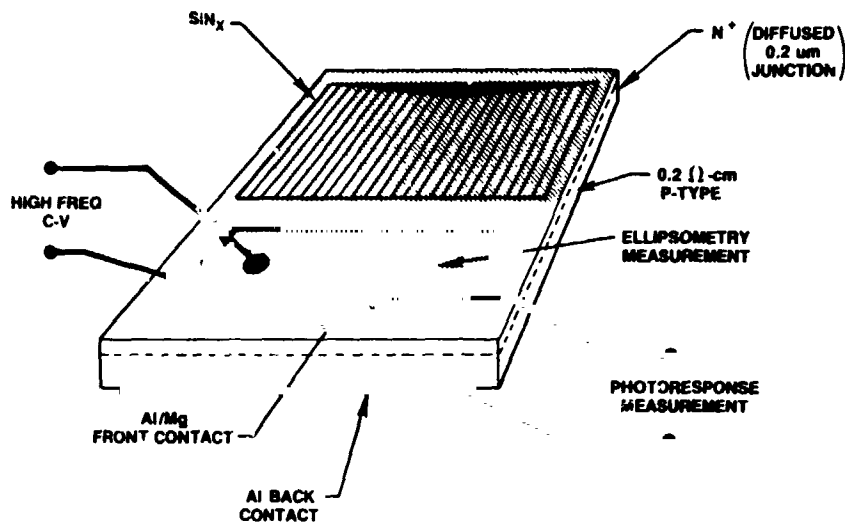
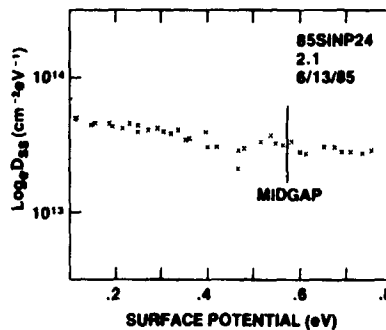
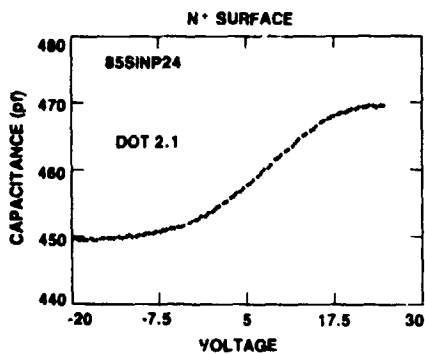
FABRICATE DEVICE STRUCTURE WITH SiN_x DEPOSITED ONTO DIFFUSED N^+ /P JUNCTIONS WHICH ALLOWS MEASUREMENTS OF:

- D_{ss} FROM HIGH FREQUENCY C-V APPLIED TO N^+ SURFACE.
- SURFACE RECOMBINATION VELOCITY FROM PHOTORESPONSE.

Processing Outline for Recombination Study

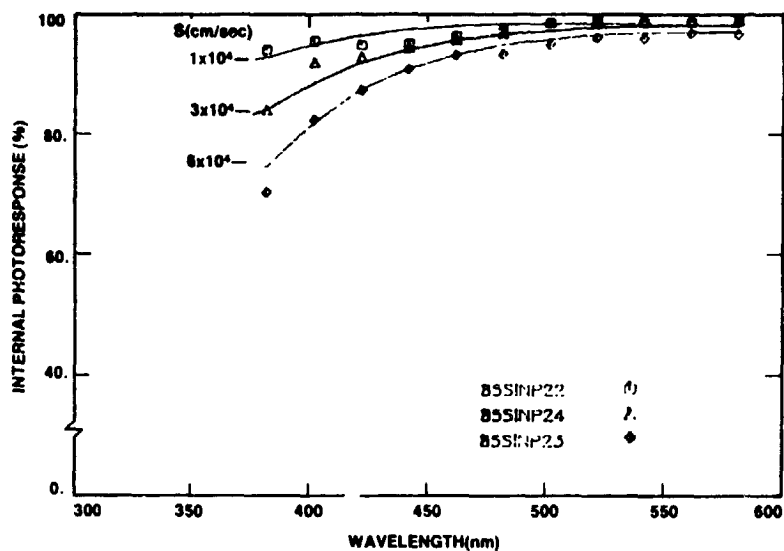


Device Structure for Surface Recombination Study

Modified Rosier Measurements: Density
of States on Surface of n^+/p Cell

HIGH-EFFICIENCY DEVICE RESEARCH

Internal Photoresponse vs Wavelength



Surface Recombination Studies

SAMPLE	OXIDE THICKNESS (Å)	SIN _x THICKNESS (Å)	ANNEAL OF SIN _x	S (cm/sec)	D _{SS} (cm ² eV ⁻¹)
85-15	NATIVE	---	---	1.0×10^4	---
85-17	NATIVE	890	---	5.5×10^4	2.5×10^{13}
85-18	NATIVE	820	H.T.	2.0×10^4	2.5×10^{13}
85-24	20 Å	---	---	3.0×10^4	---
83-23	20 Å	1020	---	6.0×10^4	2.5×10^{13}
85-22	20 Å	1030	H.T.	1.0×10^4	2.4×10^{13}
85-20	100 Å	---	---	8.0×10^3	---
85-19	100 Å	960	---	4.0×10^4	2.5×10^{13}
85-18	100 Å	1020	H.T.	9.0×10^3	2.4×10^{13}

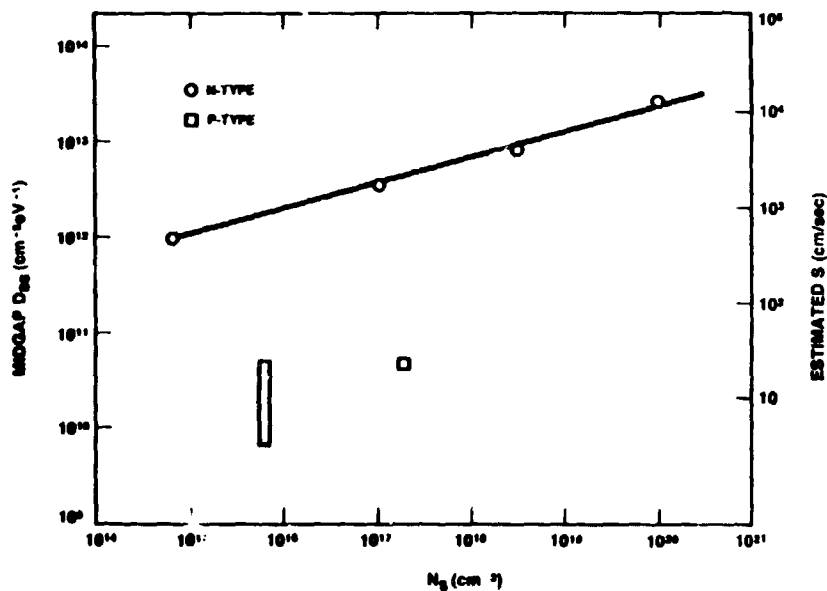
NOTES: H.T. REFERS TO HEAT TREATMENT AT 400°C FOR 15 MINUTES.

HIGH-EFFICIENCY DEVICE RESEARCH

Variation of Surface State Density With Dopant Concentration

SAMPLE RESISTIVITY (ohm-cm)	DOPANT CONCENTRATION (cm ⁻³)	D _{SS} (cm ⁻² eV ⁻¹) DEPOSITED	D _{SS} (cm ⁻² eV ⁻¹) AFTER H.T	ESTIMATED SURFACE RECOMB VELOCITY (cm/sec)
2.0 P-TYPE	7x10 ¹⁶	5x10 ¹¹	< 5x10 ¹⁰	25
0.2 P-TYPE	2x10 ¹⁷	5x10 ¹¹	5x10 ¹⁰	25
7.0 N-TYPE (P-DOPED)	7x10 ¹⁴	1.7x10 ¹²	1.0x10 ¹²	500
.08 N-TYPE (Sb-DOPED)	1.3x10 ¹⁷	3x10 ¹²	3x10 ¹²	1.5x10 ³
.01 N-TYPE (Sb-DOPED)	3.0x10 ¹⁸	8x10 ¹²	8x10 ¹²	4.1x10 ³

NOTES: (1) MEASUREMENTS ON 'MOS' STRUCTURES BASED ON PECVD SiN_x ON HOMOGENEOUSLY DOPED WAFERS.
(2) H.T. REFERS TO 40 MINUTES AT 450°C IN ARGON.
(3) ESTIMATED SURFACE RECOMBINATION VELOCITY BASED ON $\sigma = 10^{-11}$ cm².



NOTE: ESTIMATED S BASED ON $\sigma = 10^{-11}$ cm².

HIGH-EFFICIENCY DEVICE RESEARCH

Effect of Illumination on I-V Parameters

DARK CHARACTERISTICS

$$n = 1.00$$

$$J_0 = 2.1 \times 10^{-12} \text{ A/cm}^2$$

$$\phi = 1.04 \text{ eV}$$

DOMINANT LOSS MECHANISM:
EMITTER RECOMBINATION

ILLUMINATED CHARACTERISTICS

$$n = 1.10$$

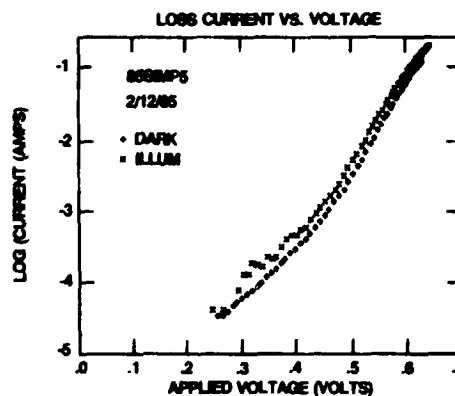
$$J_0 = 4.0 \times 10^{-11} \text{ A/cm}^2$$

$$\phi = 1.01 \text{ eV}$$

DOMINANT LOSS MECHANISM:
DEPLETION LAYER RECOMBINATION

POSSIBLE TRAP CHARACTERISTICS:

$$E_C - E_T \approx 0.2 \text{ eV} \quad N_T \approx 10^{17} \text{ cm}^{-3}$$



Depletion Layer Recombination Revisited

THEORY

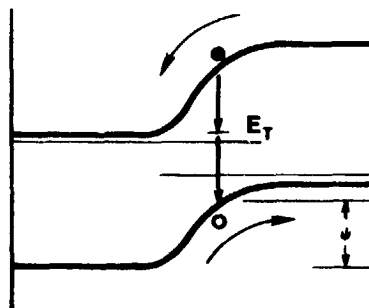
$$J_R = \int_0^W R(x) dx = \int_0^W \frac{R(\phi) d\phi}{dx}$$

$R \equiv$ Shockley - Read - Hall
Expression For
Recombination Rate

MODELING CALCULATIONS

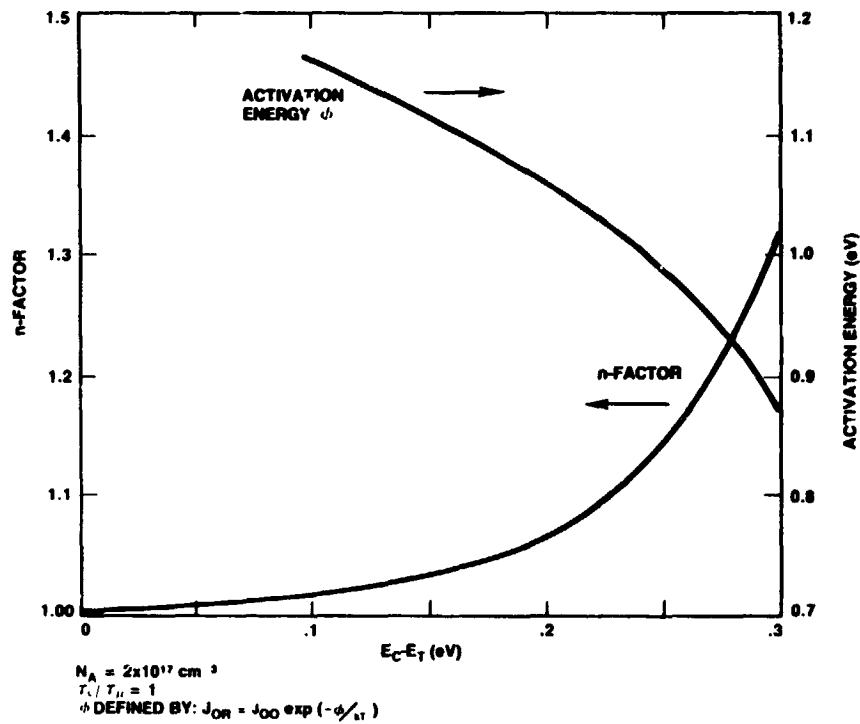
$$J_R = J_{0R} \exp\left(\frac{V}{n k T}\right) \quad V \gg k T$$

$$J_{0R} = J_{00} \exp\left(-\frac{\phi}{k T}\right)$$



HIGH-EFFICIENCY DEVICE RESEARCH

Modeling Calculations for Depletion Layer Recombination



HIGH-EFFICIENCY DEVICE RESEARCH

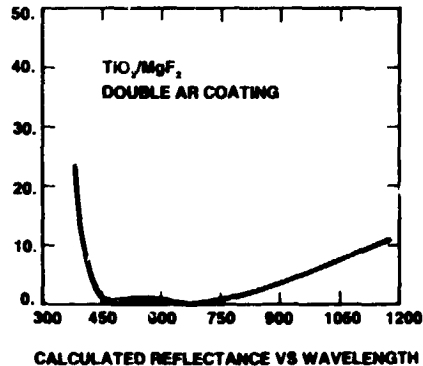
Short-Circuit Current Improvement

OBJECTIVE

- POLISHED, 0.2 Ω -cm P-TYPE SUBSTRATE
L = 150 μ m, DBLAR of TiO_2 and MgF_2 } $J_{PH} = 37.5 \frac{\text{mA}}{\text{cm}^2}$
- ASSUMING 4% SHADOWING DUE TO CURRENT COLLECTOR GRID. } $J_{SC} = 36.0 \frac{\text{mA}}{\text{cm}^2}$

STATUS

- POLISHED CELL
WITH SiO_x AR:
 $J_{SC} = 32.3 \frac{\text{mA}}{\text{cm}^2}$
- TEXTURED CELL
WITH SiO_x AR:
 $J_{SC} = 35.5 \frac{\text{mA}}{\text{cm}^2}$



PROGRESS

- DEVELOPED PROCEDURES FOR DEPOSITING TiO_2 AND MgF_2 . ELLIPSOMETRIC MEASUREMENTS WERE USED TO OBTAIN OPTICAL CONSTANTS. CALCULATED OPTIMUM FILM THICKNESSES FOR $\text{TiO}_2/\text{MgF}_2$ DBLAR COATING.
- DEVELOPED PROCEDURES FOR DEFINING FRONT COLLECTOR GRID BY LIFTOFF OF FULL METALLIZATION THICKNESS.
- DESIGNED AND ACQUIRED SHADOW MASK WHICH WILL YIELD COLLECTOR GRIDS WITH 4% SHADOWING.

Voltage Improvement

OBJECTIVE

- $FF = 0.81$ and $V_{OC} = 650 \text{ mV}$

STATUS

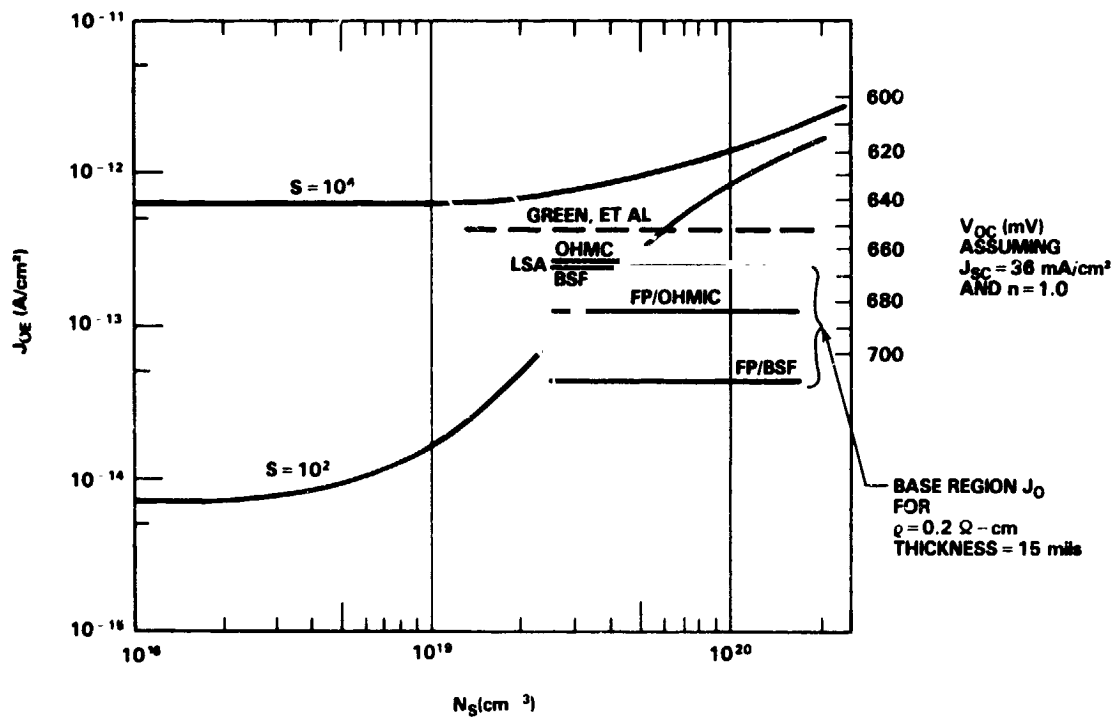
- $FF = 0.81$ and $V_{OC} = 636 \text{ mV}$

APPROACH

- EMITTER OPTIMIZATION USING ION IMPLANTATION:
 $N_s \approx 3 \text{ to } 4 \times 10^{18} \text{ cm}^{-2}$
 $R \approx 200 \Omega/\square$
- REDUCTION OF SURFACE RECOMBINATION:
 $S \approx 10^3 \text{ cm/sec.}$
- $V_{OC} = 650 \text{ mV.}$
- ASSUMING $J_{SC} = 36 \text{ mA/cm}^2$, AMI EFFICIENCY = 19.0%.

HIGH-EFFICIENCY DEVICE RESEARCH

Emitter j_0 vs Surface Donor Concentration



HIGH-EFFICIENCY DEVICE RESEARCH

Key Results

MINP SOLAR CELLS

- DOUBLE AR COATING CONSISTING OF $\text{TiO}_2/\text{MgF}_2$ AVAILABLE.
- APPROACH TO MORE OPTIMUM EMITTER CONCENTRATION PROFILE
- EFFICIENCIES: 16.3%(POLISHED), 17.0%(TEXTURED)
- VOLTAGE: $V_{OC} = 636 \text{ mV}$.

CURRENT LOSS MECHANISMS

- HAVE IDENTIFIED LIGHT ENHANCED CURRENT LOSS MECHANISM IN HIGH EFFICIENCY CELLS. CAN BE EXPLAINED BY DEPLETION LAYER RECOMBINATION.
- HAVE EXTENDED Sah-Noyce-Shockley MODELING CALCULATIONS TO INCLUDE TEMPERATURE DEPENDENT I-V CHARACTERISTICS AND ENERGY ACTIVATION ANALYSIS.

SURFACE PASSIVATION

- STUDIES OF 'MOS' STRUCTURES WITH SiN_x INSULATING LAYERS ON N-TYPE WAFERS INDICATE SURFACE STATE DENSITY CORRELATES WITH DONOR DENSITY.
- MODIFIED ROSIER MEASUREMENT DEVELOPED. INVOLVES PHOTO-RESPONSE ANALYSIS TO OBTAIN SURFACE RECOMBINATION VELOCITY AND HIGH FREQUENCY C-V TO OBTAIN SURFACE STATE DENSITY.
- DETERMINED THAT PECVD SiN_x ANNEALED AT 400°C RESULTS IN $S = 10^4 \text{ cm/sec}$ ON N^+ SURFACE WITH $N_S = 10^{20} \text{ cm}^{-3}$, SIMILAR RESULT OBTAINED WITH 100 \AA SiO_2 PASSIVATION.